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13. ABSTRACT (MAX 200 WORDS): THIS PAPER DESCRIBES A TECHNIQUE THAT ENABLES FATIGUE CRACK GROWTH RATE TO BE DETERMINED FOR A RANGE OF STRESS RATIOS, R, USING A SINGLE SPECIMEN. THE PROCEDURE ELIMINATES SOME OF THE SCATTER NORMALLY ENCOURNTERED WHEN DATA ARE OBTRAINED FROM MULTIPLE SPECIMENS. IN THE PROCESS OF VERIFYING THE PROCEDURE, THE EFFECT OF R ON THE FATIGUE CRACK GROWTH RATE IN STEEL QIN, AND THE EFFECT OF INCREASES AND DESCREASES IN R, HAVE BEEN EXAMINED. CHANGE IN THE STRESS RATIO CAUSES SIGNIFICANT CHANGE IN THE CRACK GROWTH RATE IN THE PARIS REGIME, BUT TRANSIENT EFFECTS ARE NOT OBSERVED UNLESS THE MAXIMUM STRESS INTENSITY FACTOR AT THE CRACK TIP IS REDUCED BY MORE THAN ABOUT 10%.

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Measurement of the effects of stress ratio and changes of stress ratio on fatigue crack growth rate in a quenched and tempered steel

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This paper describes a technique that enables fatigue crack growth rate to be determined for a range of stress ratios, R, using a single specimen. The procedure eliminates some of the scatter normally encountered when data are obtained from multiple specimens. In the process of verifying the procedure, the effect of R on the fatigue crack growth rate in steel Q1N, and the effect of increases and decreases in R, have been examined. Change in the stress ratio causes significant change in the crack growth rate in the Paris regime, but transient effects are not observed unless the maximum stress intensity factor at the crack tip is reduced by more than about 10%.

(Keywords: crack growth; experimental technique)

It is often stated that the rate of fatigue crack growth in metallic materials is insensitive to mean stress (or stress ratio) in the Paris regime of intermediate stress intensity factor range where the growth rate follows the relationship

$$\frac{da}{dN} = C(\Delta K)^n \quad (1)$$

where:

a = crack length;
N = number of cycles;
ΔK = stress intensity factor range; and
C and n = material constants.

While this appears to be the case at first glance, when the data are plotted on a $\log(da/dN)-\log(\Delta K)$ basis, it is well known that changes in stress ratio do in fact lead to significant changes in growth rate in the Paris regime.

In the present work an experimental technique is described that enables the steady-state fatigue crack growth rate to be measured over a range of stress ratios using a single specimen. The main advantages of the technique are:

1. reduction in the effort of sample preparation and the amount of material required; and
2. reduction in the amount of scatter normally found when comparing crack growth rate data obtained from multiple specimens.

The reduction in scatter has the advantage of revealing more clearly the extent to which changes in stress ratio affect the crack growth rate.

One of the potential problems in measuring crack growth rate at different stress ratios is the generation of transient effects when R is changed (temporary retardation or acceleration of the crack). The susceptibility of the quenched and tempered steel Q1N to transient effects was examined by varying the stress ratio in three different sequences. This work also served to confirm that the proposed technique for measuring the effect of R using a single specimen is effectively free of transient effects.

MATERIALS AND METHODS

Centre-cracked fatigue specimens were machined from quenched and tempered steel Q1N plate with the composition and properties shown in *Table 1*. After rough machining, the specimens were stress-relieved at 600°C for 1 h and then ground to final dimensions. The specimens were in the L–T orientation with a width W of 100 mm and a thickness B of 12.5 mm, according to ASTM standard E647-88.[1]

The stress intensity factor expression is

$$K = \left(\frac{P}{B\sqrt{W}}\right)\sqrt{(\theta \sec\theta)} \quad (2)$$

where:

P = load;
B = specimen thickness;
W = specimen width;
$\theta = \pi a/W$; and
a = crack length measured from the centreline of the specimen.

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Table 1 Q1N steel composition and tensile properties

%C	%Si	%Mn	%P	%S	%Ni	%Cr	%Mo	%Cu	Yield (MPa)	Ultimate (MPa)
0.16	0.25	0.31	0.010	0.0[illegible]	2.71	1.42	0.41	0.10	570	663

Fatigue loading was applied using a 2 MN Losenhausen servohydraulic machine fitted with hydraulic grips. Loading was sinusoidal at a frequency of 3–5 Hz. The test environment was laboratory air at a typical temperature of 20°C and relative humidity of 50%. Crack length was measured, relative to the positions of lines scribed on the polished surface of the specimen, using a travelling microscope with a magnification of ×40, and then converted to absolute crack length.

Crack growth was monitored during a number of intervals of constant-amplitude loading. The cracks were allowed to extend by about 4 mm during each interval, and then the load range and stress ratio were changed to begin the next interval. In this way several stress ratios were applied in a stepwise fashion to a given specimen. Four different sequences of constant amplitude load ranges were followed (i.e. four specimens in all).

Crack length a ranged from 11 mm up to about 37 mm, where the tests were terminated because the ASTM net section yielding restriction was being approached (for the fourth specimen the final crack length was only 28 mm). The load was reduced to zero at each change in stress ratio, before being reset for the next crack extension interval. In a few cases there was an overnight rest period between two crack extension intervals but this had no apparent effect on subsequent results.

The loads were initially calculated by assuming that Elber's formula[2]

$$\frac{da}{dN} = C(\Delta K_{eff})^n = C[U(R)\,\Delta K]^n \tag{3}$$

and Schijve's equation[3]

$$U(R) = \frac{0.55 - 0.2R - 0.25R^2 - 0.1R^3}{1 - R} \tag{4}$$

were applicable to Q1N steel. One of the consequences of this is that crack growth rate curves for different stress ratios are taken to be parallel when plotted as $\log(da/dN)$ against $\log(\Delta K)$ because

$$\log\left(\frac{da}{dN}\right) = \log(C) + n\log[U(R)] + n\log(\Delta K) \tag{5}$$

Crack growth rates were calculated from the raw crack length data using the seven-point incremental parabolic method. The fracture faces of the specimens were examined after testing to check for crack front curvature (negligible). The cracks in all specimens began with a flat fracture face at the starter notch but developed a slight amount of slant as the cracks grew (slant of up to 15° from the horizontal).

LOAD CALCULATIONS AND RESULTS

Basic data

The first of the four specimens was tested under a single constant-amplitude load range, at $R = 0$, to obtain the basic da/dN–ΔK curve for the steel. Results are shown in *Figure 1*. For stress intensity factor ranges in excess of 20 MPa $m^{1/2}$ the data fall on the line

$$\frac{da}{dN} = 7.14 \times 10^{-11}\,(\Delta K)^{2.26} \tag{6}$$

where the growth rate is in m $cycle^{-1}$ and ΔK is in MPa $m^{1/2}$ units.

Initial technique for measuring effect of R

The second specimen was tested by applying a stepwise sequence of six constant-amplitude load ranges. The goal was to propagate the cracks at different stress ratios, avoiding transients when the stress ratio was changed. In order to do this, the load ranges to be applied to the specimen were calculated so that there would be no (or minimal) change in the growth rate when R was changed. Of course the growth rate would still increase during the test in the same way that it does in a standard constant-amplitude

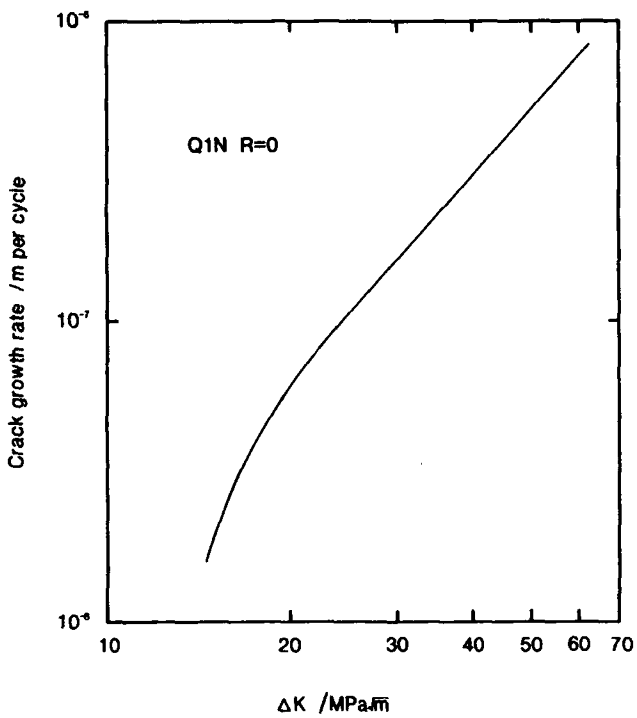

Figure 1 Basic fatigue crack growth rate curve for steel Q1N under constant-amplitude loading at $R = 0$ (specimen 1)

Table 2 Loads calculated for constant growth rate at different R

	R					
	−2	−1	−0.5	0	0.3	0.6
P_{max} (kN)	73.3	91.7	91.7	100.0	118.3	172.7
P_{min} (kN)	−146.5	−91.7	−45.8	0	35.5	103.6

test at fixed R, because of the increase in stress intensity with increase in crack length (as in *Figure 1*).

The following procedure was adopted. According to Equation (3), the crack growth rate under loading ΔK_1, R_1, will be the same as under loading ΔK_0, R_0, when

$$\Delta K_1 = \Delta K_0 \frac{U(R_0)}{U(R_1)} \tag{7}$$

With the $U(R)$ function given by Equation (4), the loads required to maintain constant growth rate at different R are as shown in *Table 2* (relative to 100 kN for $R = 0$).

The simplest strategy for avoiding transients would be to increase the stress ratio in a sequence beginning with the most negative R required, so that K_{max} would continually increase. However, in the present work the second specimen was subjected to the sequence $R = 0$, $R = -0.5$, $R = -1$, $R = 0$, $R = 0.3$, $R = 0.6$, $R = 0$ in order to evaluate the effects of decreasing and increasing R and K_{max}. The loads applied to the specimen differed slightly from those in *Table 2*, and are shown in *Table 3* in the order in which they were applied.

Results are shown in *Figure 2*. The crack growth rate steadily increased as desired until the interval of crack growth at $R = 0.3$, where the growth rate was lower than at the end of the preceding interval at $R = 0$ (because the $U(0.3)$ value used to calculate the load range was not appropriate to Q1N steel). Therefore a greater load range than initially calculated was applied during the subsequent growth interval at $R = 0.6$ (and a smaller load range in the final interval at $R = 0$).

The data do not reveal significant transient effects except for retardation of the cracks when R was reduced from 0.6 to zero for the final growth interval (owing to the large reduction in K_{max}; see *Table 3*). Increases in K_{max} or decreases of less than 10% did not cause noticeable transient effects, nor did increases or decreases in R unless this also involved a large reduction in K_{max}.

The displacements of the $\log(da/dN)$–$\log(\Delta K)$

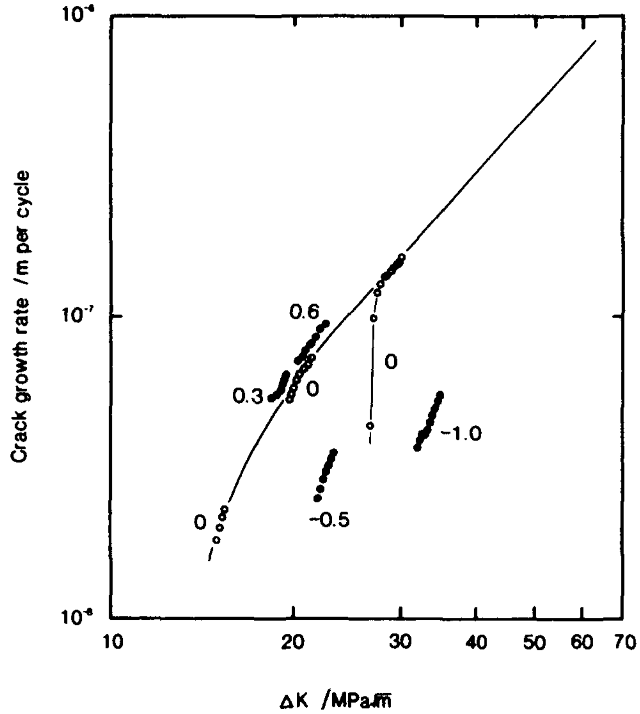

Figure 2 Fatigue crack growth rates in specimen 2, with R changed in the sequence 0, −0.5, −1, 0, 0.3, 0.6, 0 (data points), compared with results from specimen 1 (full curve)

curves in *Figure 2* from the basic $R = 0$ curve (*Figure 1*) were used to calculate the values of the function $U(R)$ relative to its value at zero stress ratio using Equation (7). The values are shown in *Table 4*. When obtained in this way, $U(R)$ is not strictly a crack closure function but merely an empirical correlation function[4]. The experimental values are in close agreement with the Schijve Equation (4) for negative R, but are much lower at positive R. Calculations of the loads required for subsequent specimens were based on the experimental values of $U(R)/U(0)$ in *Table 4*.

Preferred technique for measuring the effect of R

The technique described in the previous section appears to be a satisfactory approach to avoiding transients in the process of measuring the effect of stress ratio (provided R and K_{max} are continually increased). However, it has the disadvantages that each R step is at a different crack growth rate, and that the basic $R = 0$ crack growth rate curve is required for comparison (that is, two specimens are required). The technique described below overcomes these drawbacks.

The third specimen was tested using a sequence of constant amplitude load ranges which was designed to:

Table 3 Loads applied to specimen 2

	R						
	−0.02	−0.52	−1.04	−0.01	0.29	0.60[a]	0[a]
P_{max} (kN)	98	91	90	99	115	205	83
P_{min} (kN)	−2	−47	−94	−1	33	122	0

[a]Loads differ from *Table 2* for reasons given in text

Table 4 $U(R)$ function for Q1N (specimen 2)

	R				
	−1.04	−0.52	−0.01	0.29	0.60
$U(R)/U(0)$ expt	0.54	0.73	1.00	1.05	1.06
$U(R)/U(0)$ Schijve	0.53	0.72	0.99	1.20	1.45

Table 5 Loads applied to specimen 3

	R					
	−2	−1	−0.5	0	0.3	0.6
P_{max} (kN)	110	110	110	110	125	196
P_{min} (kN)	−220	−110	−55	0	36	117

Table 6 Loads applied to specimen 4

	R				
	0.31	0.20	0.11	0.05	−0.40
P_{max} (kN)	204	153	123	103	85
P_{min} (kN)	64	30	14	5	−34

1. maintain a crack growth rate of about 1×10^{-7} m cycle^{-1};
2. cover a range of stress ratios from −2 to +0.6; and
3. ensure that the maximum stress intensity factor increased throughout the test in order to avoid transient effects.

In order to achieve approximately constant crack growth rate the natural increase in K_{max} and growth rate with increasing crack length must be compensated by suitably adjusting the stress ratio and load range at the beginning of each interval of crack growth. There is a degree of flexibility in the allowable sequence of R values when R is negative, but for positive stress ratios it is essential that R be increased for each successive crack growth interval if K_{max} is not to decrease at any step.

The loads shown in *Table 5* were applied to specimen 3 in the sequence $R = -2$, $R = -1$, $R = -0.5$, $R = 0$, $R = 0.3$, $R = 0.6$. In calculating the required loadings, the experimental $U(R)$ function shown in *Table 4* was applied, and the values adjusted slightly to ensure that K_{max} did not decrease at any R change.

Results are shown in *Figure 3*. No transient effects are apparent. The values of $U(R)/U(0)$ derived from the data are in good agreement with those shown in *Table 4*, and will be considered in more detail below. In spite of this there was still some doubt that minor transient effects might be affecting the data. This possibility was investigated using the final specimen.

Crack growth retardation

In order to introduce transients deliberately at the beginning of the crack growth intervals, the fourth specimen was loaded so that K_{max} decreased by about 20% at each stepwise change in R. The sequence of R values was +0.3, +0.2, +0.1, 0, −0.4. The loads applied to the fourth specimen are shown in *Table 6*.

Results are shown in *Figure 4*. The crack growth is clearly retarded at each reduction in R (and reduction in K_{max}) but the growth rate quickly returns to its steady-state values (where the slope of the da/dN–ΔK curve matches that of the basic curve in *Figure 1*). Recovery occurred within about 10^4 cycles, or 1.0 mm of crack extension (a few monotonic plastic zone sizes).

DISCUSSION

The experimental $U(R)/U(0)$ values for specimens 2, 3 and 4 are compared in *Table 7*. Note that for

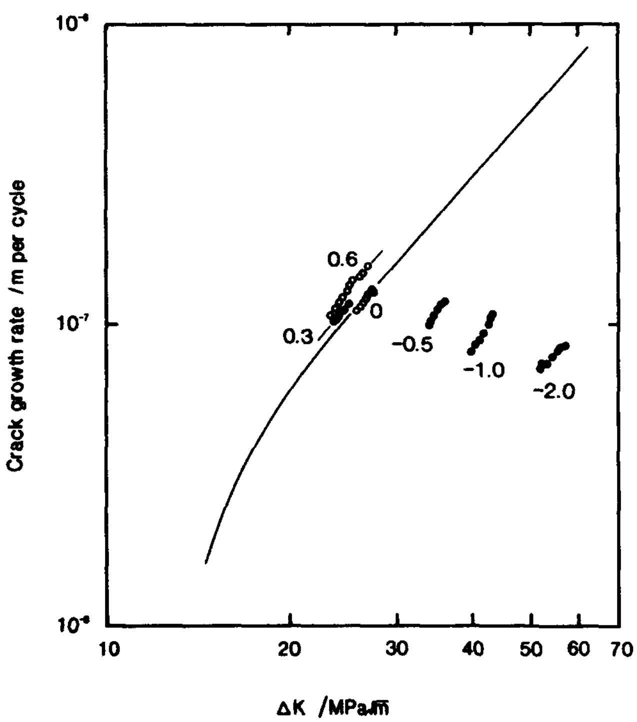

Figure 3 Fatigue crack growth rates in specimen 3, with R changed in the sequence −2, −1, −0.5, 0, 0.3, 0.6 (data points), compared with results from specimen 1 (full curve)

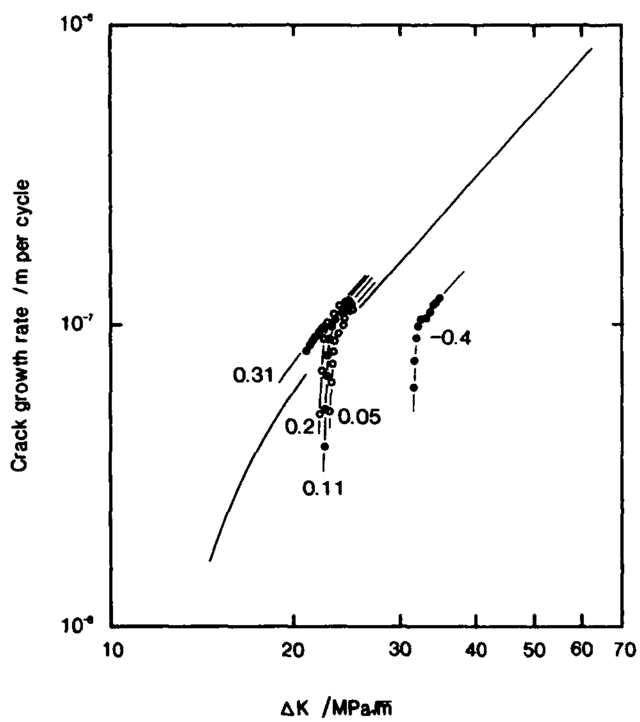

Figure 4 Fatigue crack growth rates in specimen 4, with R changed in the sequence 0.3, 0.2, 0.1, 0.05, −0.4 (data points), compared with results from specimen 1 (full curve)

Table 7 $U(R)/U(0)$ values

	$U(R)/U(0)$				
R	Specimen 2	Specimen 3	Specimen 4	Schijve	Kurihara
−2.03	–	0.40	–	0.46	0.42
−1.04	0.54	0.56	–	0.53	0.59
−0.51	0.73	0.73	–	0.72	0.75
−0.40	–	–	0.76	0.77	0.79
0	1.00	1.00	1.00	1.00	1.00
0.05	–	–	1.03	1.03	1.03
0.11	–	–	1.06	1.07	1.08
0.20	–	–	1.09	1.13	1.15
0.31	1.05	1.05	1.10	1.21	1.26
0.60	1.06	1.09	–	1.45	1.50

specimen 4 the values have been obtained from the relative displacement of the growth rate curves once steady-state conditions had been re-established (that is, the slope of the da/dN–ΔK curve matched that of the curve in *Figure 1*).

The $U(R)/U(0)$ values for specimen 4 differ only slightly from those for the other specimens, suggesting that they are little affected by the pronounced transient behaviour at the beginning of the crack growth intervals. The results give added confidence that the results from specimens 2 and 3 (with no apparent transients) are true steady-state values, free of any influence from transients.

The Schijve equation for $U(R)$ successfully correlates data for aluminium alloys[3] in the stress ratio range $[-1,0.7]$, but agrees with present data only for stress ratios between -1 and 0. It begins to break down at positive R and large negative R. The relationship

$$U(R) = \begin{cases} 1/(1.5 - R) & \text{for } R < 0.5 \\ 1 & \text{for } R \geqslant 0.5 \end{cases} \tag{8}$$

was derived by Kurihara *et al.*[5] from data for pressure vessel steels with R ranging from -5 to $+0.8$. It also diverges from the present data for Q1N at positive stress ratios (*Table 7*).

It is argued here that the preferred technique described above for measuring the effect of R is an appropriate method for measuring the effect of stress ratio on crack growth rate. A possible criticism of the approach is that it requires prior knowledge of the values of $U(R)/U(0)$ in order to calculate the loads required to maintain a roughly constant growth rate. However, this is not a major drawback because:

1. guidance can be taken from relations such as those of Schijve and Kurihara *et al.*; and
2. the loads for the next stepwise change in loading can be adjusted based on the crack growth rate obtained in the preceding crack growth interval.

CONCLUSION

A technique has been described that allows the effect of a range of stress ratios on the steady-state fatigue crack growth rate under constant amplitude loading to be measured using a single specimen. It involves a stepwise increase in R so that the maximum stress intensity at the crack tip is non-decreasing.

The procedure has been verified by testing specimens of steel Q1N. Conclusions about the behaviour of this material are as follows.

1. At constant ΔK, changes in R cause significant changes in the crack growth rate, but not as great as described by the Schijve[3] or Kurihara[5] relations.
2. Significant transient effects are not generated by increases or decreases in R unless there is a reduction in K_{max} of more than about 10%.
3. Crack growth rate transients decay as the crack advances by a distance comparable to a few monotonic plastic zone sizes.

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